REPORT 1062

INVESTIGATION OF WEAR AND FRICTION PROPERTIES UNDER SLIDING CONDITIONS OF SOME MATERIALS SUITABLE FOR CAGES OF ROLLING-CONTACT BEARINGS [1]

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SUMMARY

An investigation of wear and friction properties of a number of materials sliding against SAE 52100 steel was conducted. These materials included brass, bronze, beryllium copper, monel, Nichrome V, 24S–T aluminum, nodular iron, and gray cast iron. The metals investigated may be useful as possible cage (separator or retainer) materials for rolling-contact bearings of high-speed turbine engines. The ability of materials to form surface films that prevent welding is a most important factor in both dry friction and boundary lubrication. These surface films were probably supplied from within the structure of the cast irons by graphitic carbon and of the bronze, by lead. Monel, Nichrome V, and beryllium copper formed films, believed to be oxides, under dry and lubricated conditions. When present, the films improved the performance of these materials.

On the basis of wear and resistance to welding only, the cast irons (nodular iron and gray cast iron) were the most promising materials investigated; they showed the least wear and the least tendency to surface failure when run dry, and when boundary lubricated they showed the highest load capacity. On the basis of mechanical properties, nodular iron is superior to gray cast iron.

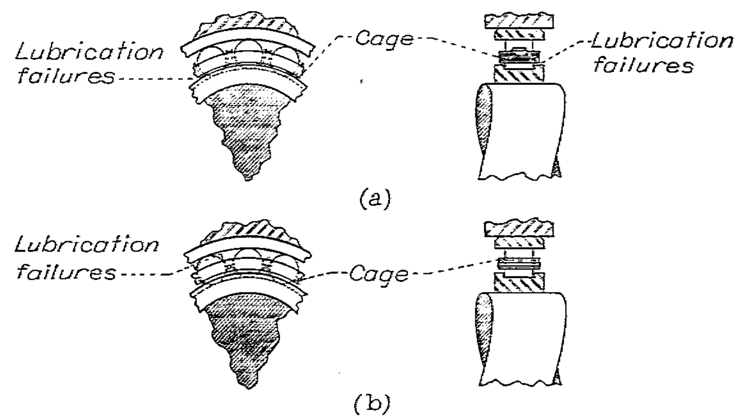
Under dry sliding conditions, bronze had the lowest friction coefficient although the material was subject to surface failure at high sliding velocities and at high loads.

The results with brass, beryllium copper, and aluminum were poor and these materials do not appear, with regard to friction and wear, to be particularly suited for cages.

INTRODUCTION

Most of the bearings employed in turbine-type aircraft engines are rolling-contact bearings. Early service experience (reference 1) indicates that the frequency of turbine-bearing failures presents a serious problem. One of the principal sources of failure in bearings has been the cage (separator or retainer). References 2, 3, 4, and service experience show that these failures are lubrication failures at the cage-locating surfaces, as indicated in figure 1.

Inadequacies in the lubrication of cages result from several factors. When the engine is shut down, "high-temperature soaking" (above 500° F) of the turbine bearing causes vaporization of the residual lubricant (Gurney's discussion, reference 4). The resulting surface may be relatively clean and dry so that during the subsequent starting of the engine, the cage and other bearing parts are operating under conditions of dry friction. Also, the cage-locating surfaces, which are those most subject to failure, are very difficult to lubricate because of their configurations. For example, when the cages are of the race-located type (either inner or outer), the mating surfaces of the cage and the race form (fig. 1(a)) a journal bearing of such extremely low length-diameter ratio L/D that it is unlikely that a hydrodynamic film of lubricant would be obtained. In addition to the anticipated loads from its function as a separator and from centrifugal forces, lubrication, in many cases, is complicated by unpredictable loads resulting from thermal distortion, misalinement of the rolling elements, and vibration. The combined effect of these conditions is the occurrence of extreme boundary lubrication and metallic adhesion, which is a frequent cause of surface failure. The trend in design of turbine-type engines is toward higher operating temperatures, higher surface speeds, and less viscous lubricants. These factors will serve to increase the severity of the cage problem for rolling-contact bearings.



(a) Inner-race-riding cage.
(b) Roller-riding cage.

Figure 1.—Location of lubrication failures at cage-locating surfaces of rolling-contact bearings.

Without changing cage design and keeping proper strength in the materials, one obvious means of reducing the severity of the problem is to obtain a more satisfactory cage material; that is, a material having a lesser tendency toward metallic adhesion to steel under marginal conditions of lubrication than the materials in current use. The currently used materials include, among others, brass, various bronzes, monel, and silver-plated bronze. It is considered that a desirable cage material might have mechanical properties approxi-

[1] Supersedes NACA TN 2384, "Preliminary Investigation of Wear and Friction Properties Under Sliding Conditions of Materials Suitable for Cages of Rolling-Contact-Bearings" by Robert L. Johnson, Max A. Swikert, and Edmond E. Bisson, 1951.

mately equivalent to the materials in current use but with superior friction and wear properties under difficult lubrication conditions. Friction coefficient is important in high-speed bearings because sliding surfaces are a source of appreciable heat generation.

The research reported herein was conducted at the NACA Lewis laboratory during 1950 to study the friction and wear properties of several materials that could be considered for use in the manufacture of rolling-contact-bearing cages. The sliding-friction experiments described herein were not simulated cage tests but were made to obtain fundamental comparative information on friction and wear properties, which are a general measure of adhesion.

Both the friction and wear experiments were conducted with loaded hemispherically shaped specimens of varied materials sliding in a continuous path on rotating steel disk specimens. Sliding velocities up to 18,000 feet per minute and loads from 50 to 1593 grams were used. The materials studied include brass, bronze, gray cast iron, nodular cast iron, monel, Nichrome V, beryllium copper, and 24S–T aluminum. Data were obtained under both dry and boundary-lubricated conditions.

MATERIALS

The reasons for selection of the various materials were different and were based on both present and anticipated requirements for cages. The materials selected have mechanical properties that are comparable with or better than those of materials in present use. A dependable calculation of the strength requirement for cages is impossible because, as previously mentioned, all the variables cannot be evaluated. For example, studies of cages from turbine roller bearings indicate that, under certain conditions, skewing of the rollers introduces end loading sufficient to cause plastic flow of an aluminum bronze cage material having a yield strength of approximately 35,000 pounds per square inch.

The materials used in the experiments reported herein are readily available materials having mechanical and physical properties that may be suitable for cages of rolling-contact bearings. The materials studied and some of their typical properties are listed in table I. The data for brass, beryllium copper, and monel were obtained from reference 5; the data for bronze, Nichrome V, and aluminum were obtained from reference 6; the data for nodular iron and gray cast iron were obtained from the Ford Motor Company and the Koppers Company, respectively.

Brass and bronze were studied because thay represent the materials most commonly used for cages at present. Beryllium copper is included in this investigation because it has good mechanical and physical properties and because very little information is available on its friction characteristics. A number of uses of this material in lubrication problems have been reported, but specific performance data are lacking.

Discussion with representatives of the bearing industry, engine manufacturers, and the armed services have indicated that monel in various forms and with slightly varied compositions has been used for cages with inconsistent results. Consideration of this material is justified not only by the questions arising from its current usage but also because it has mechanical and physical properties superior to those of bronzes at higher temperatures.

The anticipated requirement of bearings to operate at higher temperatures than the present limit of 350° F emphasizes the need for cage materials that retain their physical properties at elevated temperatures. Nichrome V was selected because of this factor, although little was known about its frictional properties.

Aluminum bearing alloys are reported (reference 7) to have antiscore properties that are comparable with those of bearing bronzes. The mechanical strengths of these bearing alloys are low, however, and this factor as well as high expansion coefficient and low modulus of elasticity may prevent their widespread use in cages. Other aluminum alloys such as 17S–T have been employed as cage materials. The experiments reported herein were conducted with 24S–T aluminum alloy, which has physical properties that are superior to those of the aluminum bearing alloys and 17S–T; 24S–T, however, undoubtedly has less desirable friction properties than the bearing alloys.

Cast iron is known to be an effective material for boundary-lubricated surfaces because the free graphitic carbon present provides a self-lubricating function that can compensate for marginal lubrication. The objections to the use of cast iron for cages are based on its brittleness and low strength. Nodular iron (reference 8) has physical properties that are more favorable than those of standard cast iron. For example, the impact strength of the material used in these experiments is 40 foot-pounds at room temperature; by heat treatment, this strength can be increased to 183 foot-pounds. In comparison, standard cast iron has an impact strength of 13 foot-pounds (reference 8, p. 431).

The disk material in all cases was SAE 52100 steel heat-treated to a hardness of Rockwell C–60. This steel is used in most rolling-contact bearings for aircraft turbine engines.

The specific compositions employed in these experiments are not necessarily the best of the respective types. The materials were selected because of immediate availability and the results are to be used in determining which materials merit further investigation.

APPARATUS AND PROCEDURE

Specimen preparation.—In each experiment there were two specimens, the rider and the disk. The final rider specimens of the materials being investigated were cylindrical (3/8-in. diam., 3/4-in. length) and had a hemispherical tip (3/16-in. rad.) on one end. The surface of the rider specimens was finished by fine turning using minimum material removal per cut in order to minimize surface cold working.

The disk specimens (13-in. diam.) were circumferentially ground on a conventional surface grinder with light grinding pressures to produce a surface roughness of 10 to 15 rms as measured with a profilometer. These roughness values are within the range of roughness measurements obtained on the cage locating surfaces of rolling-contact bearings.

The rider specimens were cleaned before each experiment with a clean cloth saturated with redistilled 95-percent ethyl alcohol. The disk specimens were carefully cleaned to remove all grease and other surface contamination according to the detailed procedure given in reference 9. Briefly, this cleaning procedure includes scrubbing with several organic solvents, scouring with levigated alumina, rinsing with water, washing with ethyl alcohol, and drying in an uncontaminated atmosphere of dried air.

Friction apparatus.—The friction apparatus used for these experiments is essentially the same as that described in reference 9. A diagrammatic sketch of the apparatus showing the holder assembly for the rider specimens and the rotating disk specimen that are the primary parts is presented in figure 2. The disk is rotated by a hydraulic-motor assembly that provides accurate speed control over a range of sliding velocities from 75 to 18,000 feet per minute. In the wear runs, loading was accomplished by placing weights on the rider holder; in the friction runs, loading was accomplished by pneumatically loading a flexible diaphragm attached to the end of the rider holder. Friction force was measured by four strain gages mounted on a beryllium copper dynamometer ring and connected to an observation-type potentiometer converted for use as a friction-force indicator. The strain gages were so mounted that temperature compensation was obtained. The coefficient of friction μ_k is calculated from the equation $\mu_k=\frac{F}{P}$, where F is the measured friction force and P is the applied normal load. The reproducibility in the coefficient of friction values in all but isolated cases was within ± 0.04 for the dry surfaces and within ± 0.02 for the lubricated surfaces. The data presented are complete data from a representative experiment on each variable.

A permanent record of the friction force variation was obtained on movie film for subsequent analysis. The disk specimen is mounted on a flywheel assembled with its shaft supported and located by a mounting block containing bearing assemblies for accurate location.

Methods of conducting experiments.—Wear runs of 3-hour duration were made on dry surfaces with loads of 50 and 269 grams at a sliding velocity of 5000 feet per minute. The complete run was made over the same wear track (without radial traverse of the rider specimen). Wear of the rider (the hemispherically tipped specimens of the materials being investigated) was determined from measurements of wear-spot diameter made with a calibrated microscope and by a weight loss obtained with an analytical balance. The final wear-volume measurements could generally be reproduced within ± 10 percent in different experiments on a given material. Weight-loss measurements were used as a check on the accuracy of the wear-spot-diameter data. Because the rider specimen tip was hemispherically shaped, wear volume was calculated from the measured wear-spot diameter. Wear volume was used in presenting all wear data because it is a convenient fundamental measure. Differences in density could cause an unfair comparison on a weight loss basis for all materials, for example, aluminum (density, 0.100 lb/cu in.) and bronze (density, 0.314 lb/cu in.). No wear measurements were made of the slider (disk) specimen.

The friction runs on dry surfaces were made with a load of 100 grams at sliding velocities from 75 to 18,000 feet per minute. In conducting the friction runs, the disk was rotated at a predetermined speed and the rider was brought into contact by pneumatically loading a calibrated diaphragm.

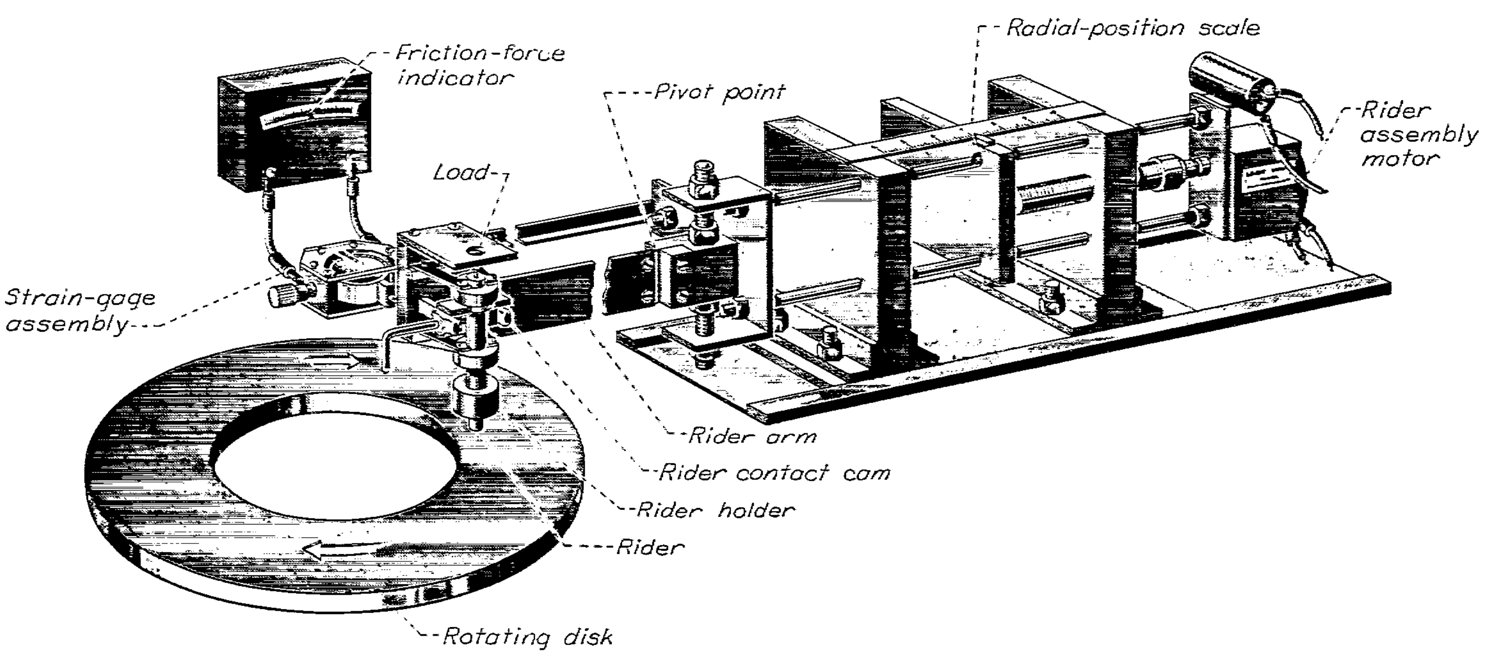


FIGURE 2.—Schematic diagram of sliding-friction apparatus.

The duration of the loading, the operation of the force-recording camera, and the operation of an electric revolution counter were controlled by a synchronized timer set for a 3-second operational cycle. All friction runs for a given material in a single experiment were made over the same wear track (without radial traverse). The sequence of the runs was arranged so that the severity of conditions (speed and load) was progressively increased.

The loads and the specimen shapes were so chosen as to produce relatively high surface-contact stresses initially. In spite of the relatively light loads that normally occur and large apparent areas of contact of the cages at their locating surface in rolling-contact bearings, the actual contact stresses can be large. As discussed in more detail in reference 10, surfaces under nominal load and with large apparent areas of contact can have stresses at the localized contact areas that are equal to the "yield pressures" (flow pressure) of the materials at the contacting asperities.

Friction runs to determine the effect of loading were made with boundary-lubricated surfaces at a sliding velocity of 5000 feet per minute; loads were increased in increments from 119 grams to the failure point of the specimens. The disk was lubricated before each 3-second run by rubbing a very thin film of a petroleum lubricant grade 1005 (Air Force specification 3519, Amendment 2) on the rotating surface with lens tissue. Previous experience at this laboratory has indicated that the film thus formed is sufficiently thin that hydrodynamic lubrication will not occur. Reference 11 shows that a lubricant film of this type may approach a monomolecular film at the points of the surface asperities. Surface failure was established by both increased friction values and the occurrence of welding (visible metal transfer).

Although most of the values reported in table I are published data, the hardnesses were checked with a Rockwell superficial hardness tester. Initial surface-roughness values for the disks were obtained with a profilometer.

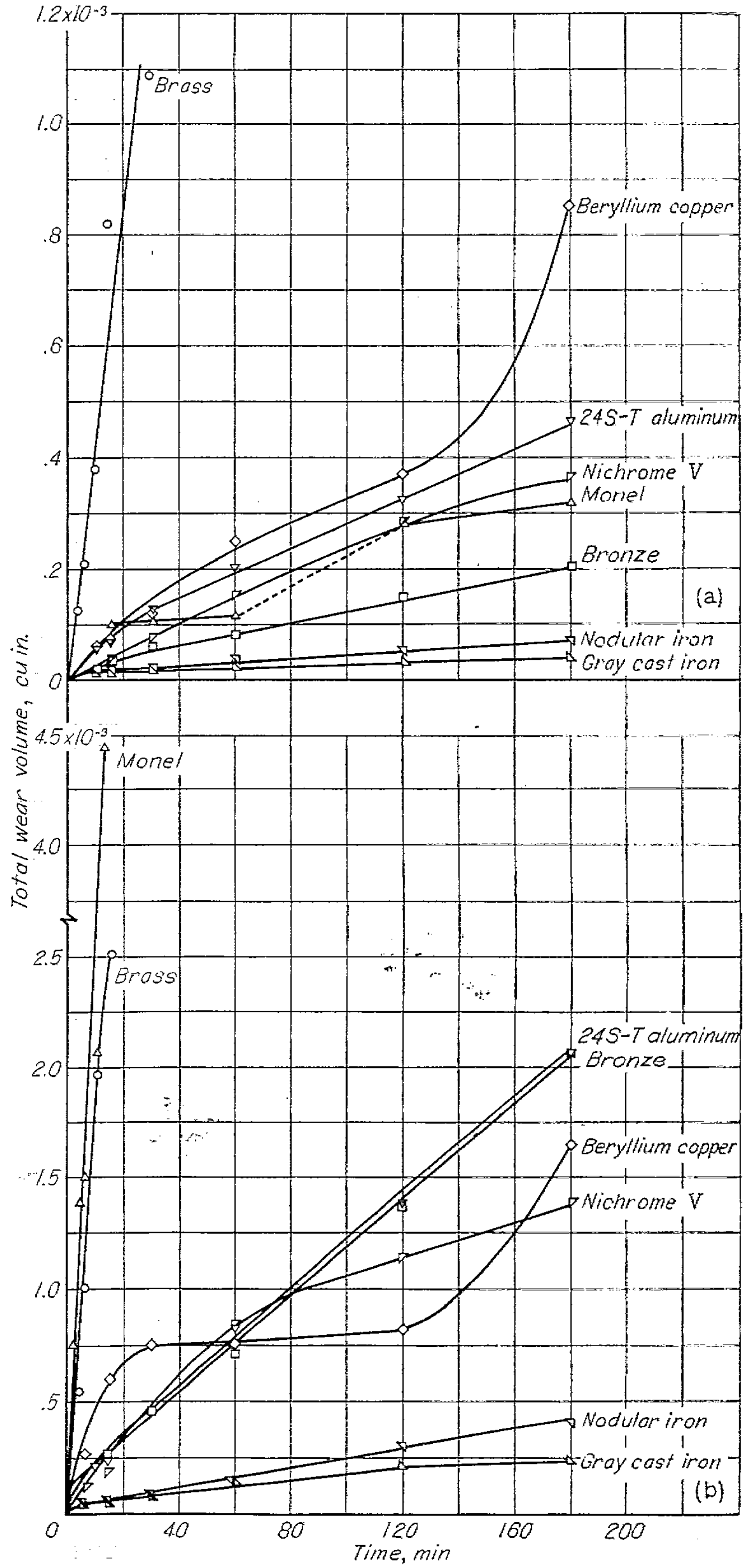
RESULTS AND DISCUSSION

The data of figures 3(a) and 3(b) show the total wear volume at different time increments up to 3 hours for each material at a sliding velocity of 5000 feet per minute with loads of 50 and 269 grams. At both loads the cast irons had better wear properties than all the other materials, whereas brass was consistently poor. Load made a great difference in wear of monel; at the higher load, it was the poorest material of the group, whereas at the lower load, its wear was less than that of some of the other materials. The apparent discontinuity in the curve for monel at the lighter load (fig. 3 (a)) and the shapes of the curves for beryllium copper obtained at both loads are factors that will be discussed later with regard to the characteristic film forming property of those materials which was observed in this research.

The difference in loads of these wear runs had an appreciable effect on the relative wear rates (slopes of the curves) of the bronze material. With the light load, bronze gave good wear results; with the heavier load, it was no better than most other materials.

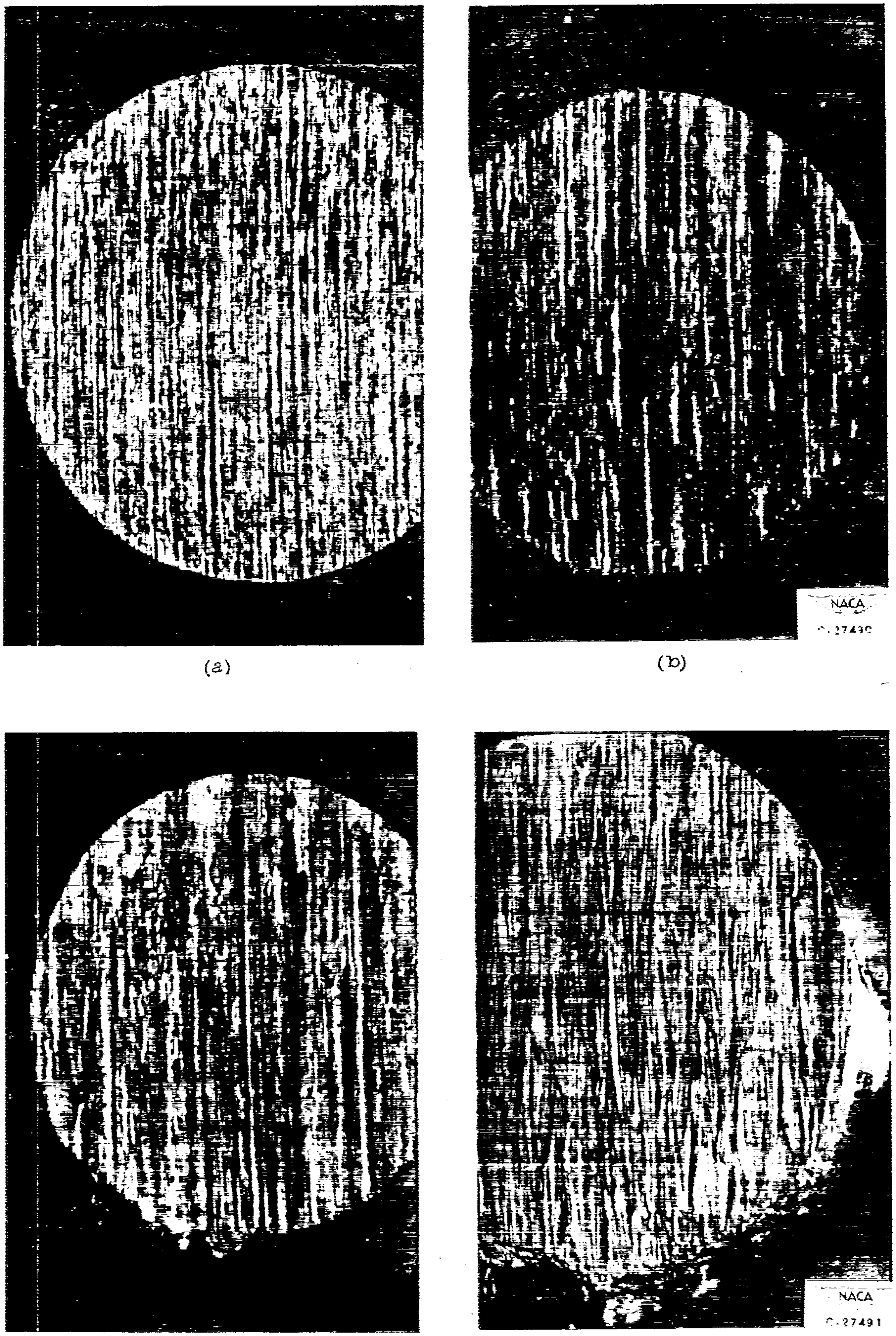
The relative amounts of total wear volume (fig. 3(b)) in percentages of the wear volume for bronze after wear runs at a load of 269 grams are as follows:

Material	Bronze	24S-T aluminum	Beryllium copper	Nichrome V	Nodular iron	Gray cast iron
Wear relative to bronze, percent	100	102	80	68	20	12



(a) Load, 50 grams.
(b) Load, 269 grams.

FIGURE 3.—Wear of several materials sliding against hardened SAE 52100 steel. Sliding velocity, 5000 feet per minute.



(a) (b)

(c) (d)

(a) Brass (15 min operation).
(b) Bronze.
(c) Beryllium copper.
(d) Monel (15 min operation).

FIGURE 4.—Wear areas of rider specimens of various materials after 3 hours sliding (unless noted) against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 269 grams; X15; reduction factor, 13 percent in reproduction.

(e) 24S-T aluminum.
(f) Nichrome V.
(g) Nodular iron.
(h) Gray cast iron.

FIGURE 4.—Concluded. Wear areas of rider specimens of various materials after 3 hours sliding (unless noted) against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 269 grams; X15; reduction factor, 13 percent in reproduction.

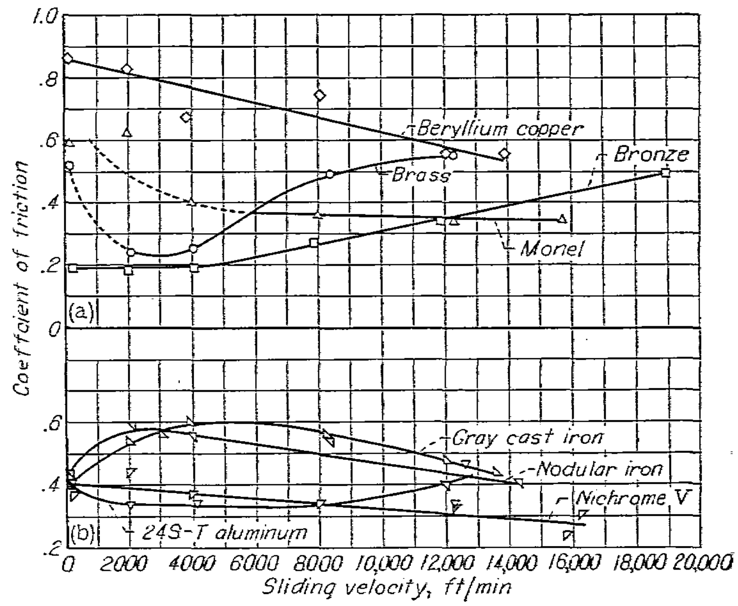
At the lighter load (50 grams), the relative wear positions of the materials changed appreciably with monel and bronze exhibiting more favorable wear properties. The cast irons had better wear properties than any of the other materials at both loads.

During the wear runs most materials had relatively stable friction values except for the initial 30 minutes of operation, when some slight increasing as well as decreasing trends were observed. Important exceptions are beryllium copper and monel. These materials had changing friction values as well as the changing wear rates previously mentioned. In studying the surfaces during the experiments, it was observed that when friction and the wear rate were low, a film had been formed on both the contacting surfaces. With beryllium copper as the rider material, the film was red to purple in color and is believed to be an oxide of copper (Cu_2O). Monel formed a black film, also believed to be an oxide. The film formed by the beryllium copper seemed more plastic in nature and more tenacious than that formed by the monel. Some tendency to film formation was also observed for Nichrome V. The film formed by Nichrome V physically resembled that formed on monel, which leads to a supposition that both films were an oxide of nickel.

Examination of the wear tracks formed on steel-disk specimens revealed that the cast irons were the only materials that did not have appreciable metal transfer to the disk surface. Cast iron formed black films that may have been graphitic carbon. No severe scoring of the steel surface was observed in the dry runs with any of the materials.

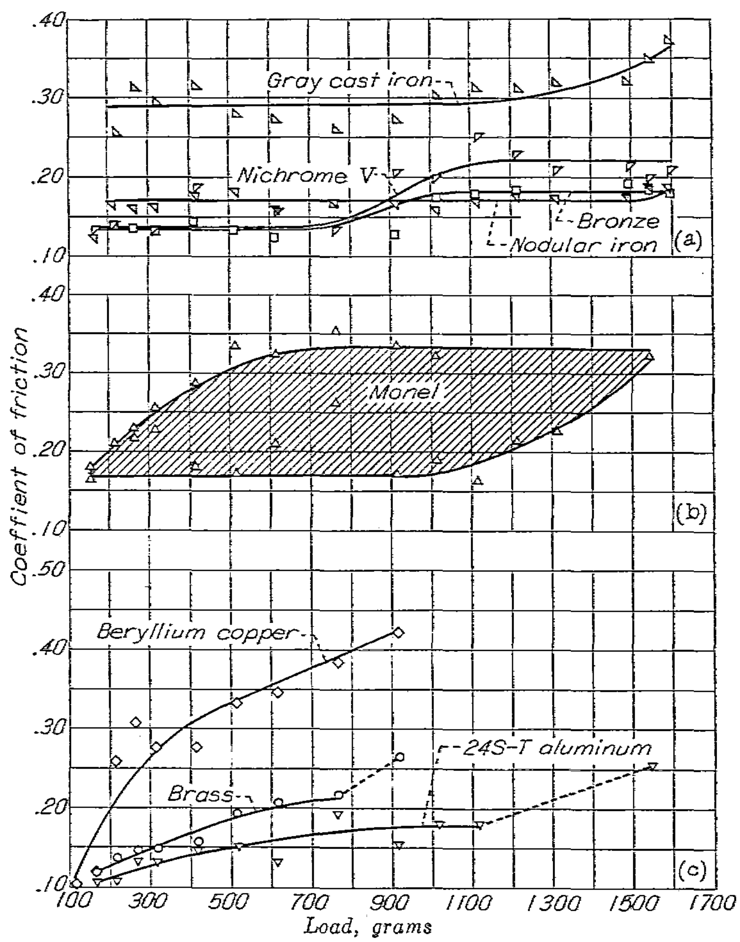
Photographs of wear areas of rider specimens of the various materials after 3 hours of operation without lubrication at a sliding velocity of 5000 feet per minute with a load of 269 grams are shown in figures 4(a) to 4(h). Brass (fig. 4(a)) and monel (fig. 4(d)) wore excessively during these experiments and consequently those runs were stopped after 15 minutes of operation. Wearing of the brass was primarily simple abrasion although this abrasion was undoubtedly accelerated by surface welding with the steel disk. Dark areas on the bronze rider (fig. 4(b)) are evidence of film formation on the surface. The film prevented severe surface damage to both the rider and the disk specimens; this film may have been supplied from within the structure of the bronze by lead. The built-up surfaces, as shown in figure 4(c), are apparently a result of transfer of beryllium copper from the disk surface; this material was transferred to the disk during the initial period of operation and was later rewelded to the rider surface. Dark streaks of the surface indicate the presence of a film. Some indication of plastic flow is apparent at the trailing (bottom) edge of the wear area (fig. 4(c)). This surface flow is not comparable, however, with that found for monel (fig. 4(d)). The plastic flow of the monel rider accompanied very rapid wear and severe welding to the disk surface.

The aluminum rider shown in figure 4(e) wore quite rapidly, showed some plastic flow, and readily welded to the steel disk. The Nichrome V specimen (fig. 4(f)) formed a



(a) Rider specimens of brass, bronze, beryllium copper, and monel.
(b) Rider specimens of 24S-T aluminum, Nichrome V, nodular iron, and gray cast iron.

FIGURE 5.—Effect of sliding velocity on kinetic friction of several materials sliding on hardened SAE 52100 steel without lubrication. Load, 100 grams.



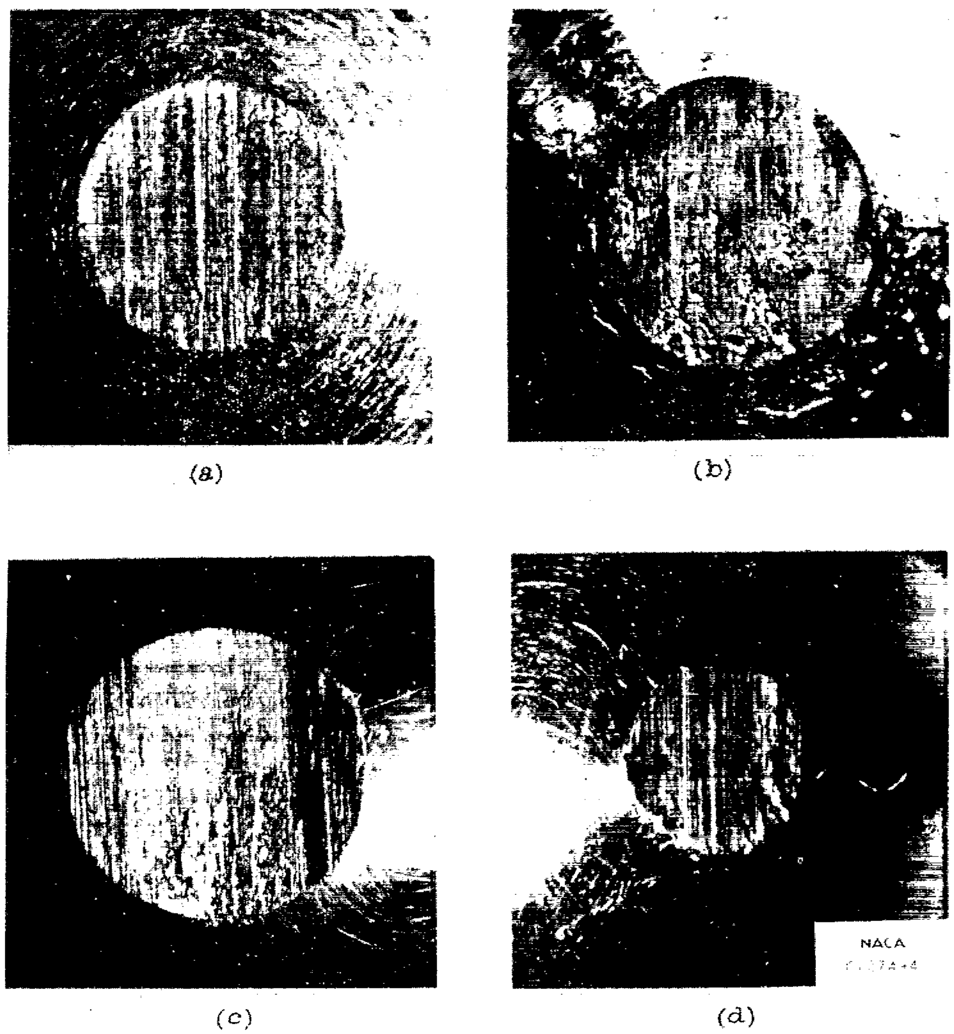
(a) Rider specimens of nodular iron, Nichrome V, bronze, and gray cast iron.
(b) Rider specimen of monel.
(c) Rider specimens of 24S-T aluminum, beryllium copper, and brass.

FIGURE 6.—Effect of load on friction of several materials sliding on hardened SAE 52100 steel boundary lubricated with grade 1065 turbine oil. Sliding velocity, 5000 feet per minute.

black oxide film (possibly a nickel oxide), which may have prevented more severe surface damage. Film-formation properties proved to be beneficial in the case of the two cast-iron materials, nodular iron and gray cast iron (figs. 4(g) and 4(h)). The materials formed films (believed to be graphitic carbon) on the surfaces of the riders and the disks, which prevented harmful welding and excessive wear.

Dry friction.—In figure 5 is shown the effect of sliding velocity on friction at a load of 100 grams for all the materials investigated. Brass (fig. 5(a)) exhibited unstable friction coefficient trends. Beryllium copper (fig. 5(a)) had an unusually high friction coefficient, although surface failure and metal transfer were not so severe as with several other materials. Dashed lines for the low-sliding-velocity section of the monel curve indicate unstable friction values that occurred while the surface film was forming. At higher loads, the film formed more rapidly and during the short duration of the friction runs did not completely fail. Bronze showed the lowest initial friction values; however, its frictional properties changed above 4000 feet per minute as the material began to fail with increased severity of sliding. Nichrome V showed relatively stable friction coefficient values at all conditions (fig. 5(b)). The aluminum alloy (24S-T) showed low friction coefficients in view of the large amount of surface welding and metal transfer that occurred. Both gray cast iron and nodular iron showed surprisingly high friction values in spite of the fact that the transferred graphite film prevented surface welding of any magnitude.

Effect of load with lubricated surfaces.—A series of runs was made (fig. 6) with the materials being run on boundary-lubricated disk surfaces at a sliding velocity of 5000 feet per minute with loads increased in small increments until surface failure occurred. Incipient surface failure of the rider wear area was generally observed when friction began to increase

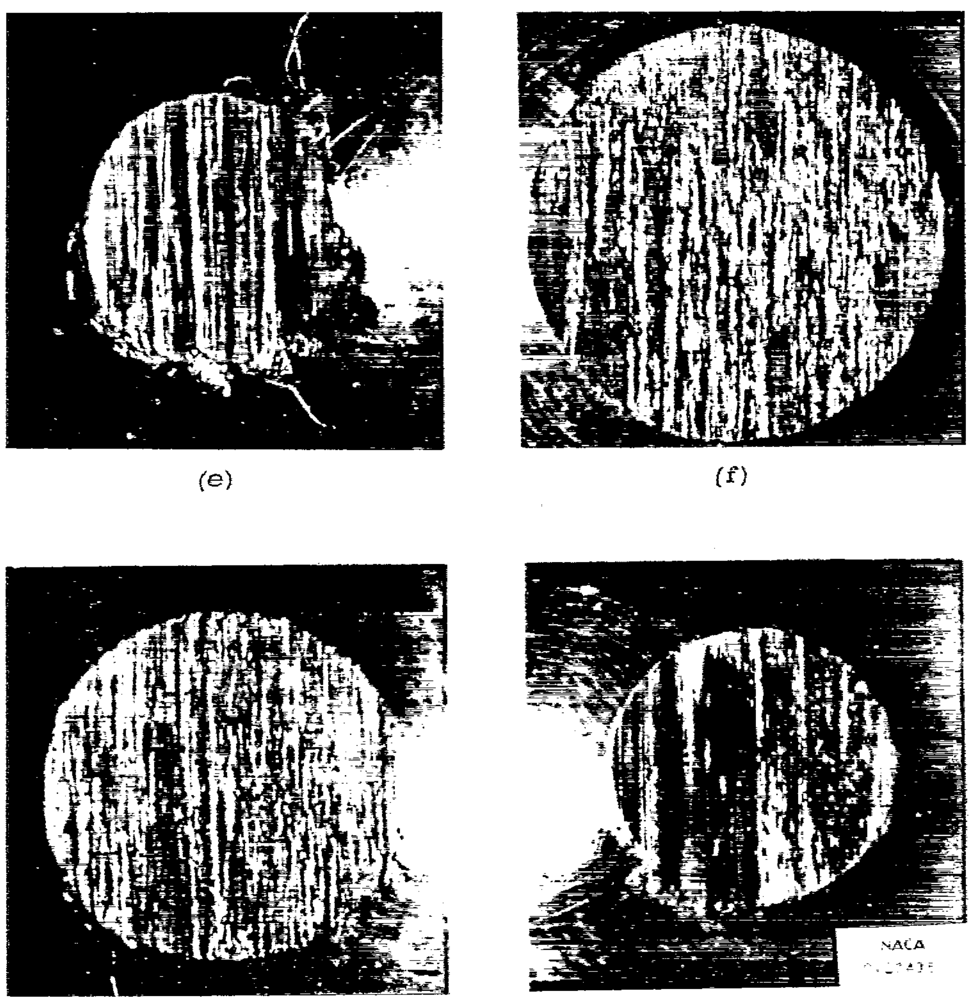


(a) Nodular iron.
(b) Gray cast iron.
(c) Bronze.
(d) Nichrome V.

FIGURE 7.—Wear areas of rider specimens of various materials after similar series of friction experiments with hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute; load, 119 to 1593 grams; X15; reduction factor, 13 percent in reproduction.

with greater loads (fig. 6); that is, when the results deviated from Amonton's law. For those materials (bronze, Nichrome V, and the cast irons) which produced friction results obeying Amonton's law, mass surface failure accompanied an abrupt increase in friction coefficient. In several cases this did not occur until there had been incipient failure through a considerable range of loads.

The following discussion is based both on visual study of the specimens as the runs progressed and on the friction data of figure 6. The cast irons supported greater loads without failure than any of the materials investigated. With the highest load used, friction increased slightly (fig. 6 (a)). The friction data indicate that bronze showed incipient failure with loading approaching 800 grams and the appearance of the surfaces showed that mass surface failure did not occur until loads over 1400 grams were applied. Nichrome V did not show any mass surface welding; incipient surface failure was observed at loads above 800 grams. Film formation with Nichrome V appeared to be very beneficial. After incipient failure, the film continued to form and at progressively higher loads friction leveled out. Preformation of the film material on Nichrome V and other materials showing film-formation properties might be an effective means of making the material suitable for cages because the film might be regenerated in service. The friction data for monel (fig. 6 (b)) were inconsistent throughout the range of effective lubrication and the spread of friction values was quite large. This behavior may be a result of the tendency of the surface oxide film alternately to form and to break down during sliding. Brass, beryllium copper, and the aluminum alloy showed incipient failure at the lightest loads used in these experiments (fig. 6 (c)). Brass progressed to the stage of mass surface welding at loads above 800 grams and friction increased appreciably. Aluminum did not show any marked



(e) (f)

(g) (h)

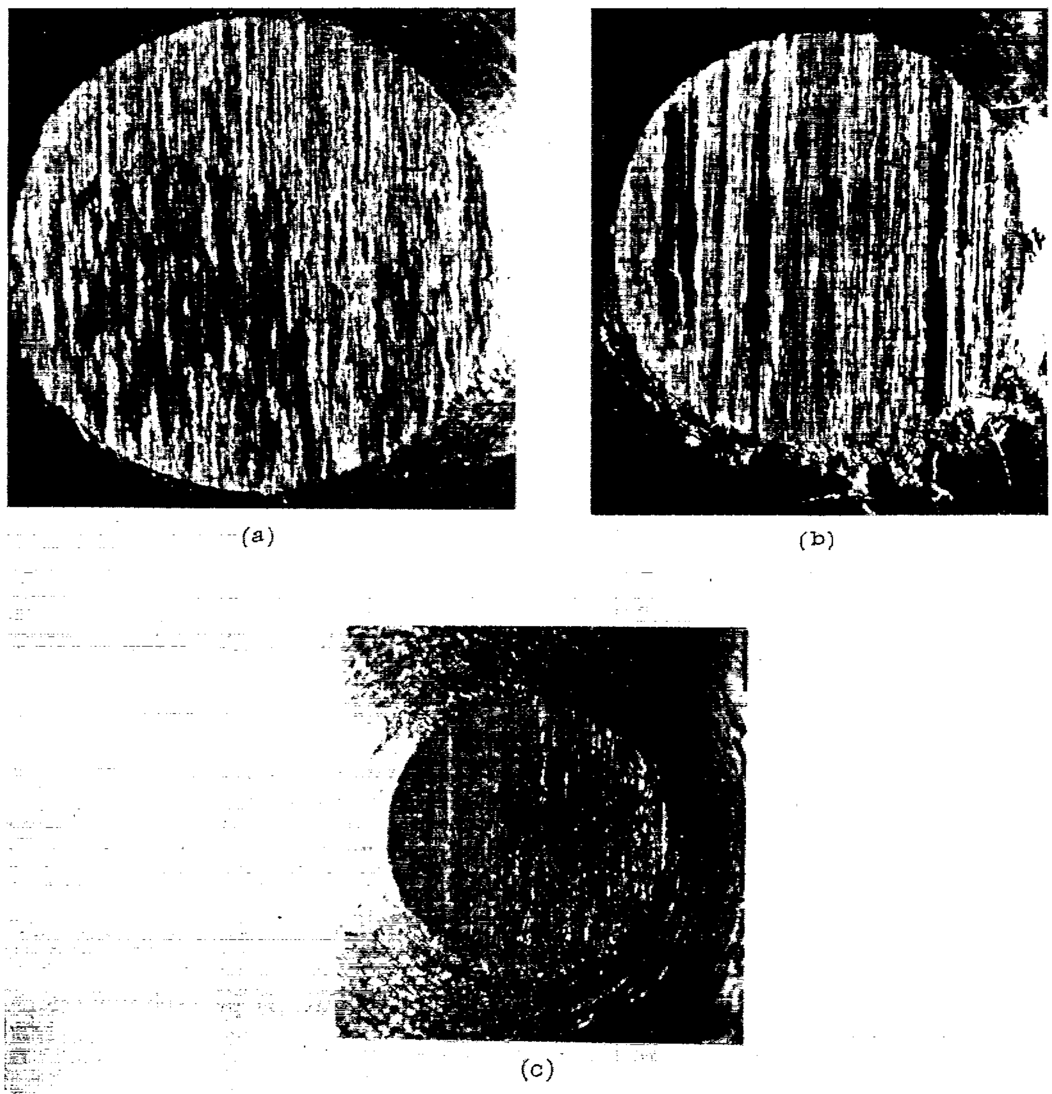
(e) Monel. (f) Brass.
(g) Beryllium copper. (h) 24S-T aluminum.

FIGURE 7.—Concluded. Wear areas of rider specimens of various materials after similar series of friction experiments with hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute; load, 119 to 1593 grams; ×15; reduction factor, 13 percent in reproduction.

transition from incipient to mass welding, but considerable amounts of metal transfer occurred at loads above 1100 grams and friction increased appreciably. Friction of beryllium copper was very high and the material failed with relatively light loading; after the red film formed at the higher loads or with continued operation, however, wear of the lubricated surface was low and little surface welding occurred unless the surface film broke down. Figure 7 is a series of photographs of wear areas of rider specimens after the complete friction experiments from which the friction data presented in figure 6 were obtained. The photographs of figure 7 generally confirm the results of the visual observations discussed in this paragraph.

Film-formation properties.—Throughout the experiments reported herein with both dry and lubricated surfaces, the occurrence of built-up films, which are presumably oxides, had marked effects on wear and surface failure properties of monel, Nichrome V, and beryllium copper. This film formation may be a factor that could explain the inconsistent service results that have been obtained with monel cages for rolling-contact bearings. Friction data reported herein showed inconsistent values attributable to formation and failure of surface films. A study of the means of controlling the formation of these films could have significant results. This statement may be particularly true for Nichrome V, which has physical properties of interest for high-temperature bearings.

The Nichrome V rider (fig. 4(f)) showed film formation after operation for 3 hours at a sliding velocity of 5000 feet per minute with a load of 269 grams. Under those conditions, the films formed on beryllium copper and monel were not sufficiently adherent to remain on the wear area until the end of the experiment. Figures 8(a) and 8(b) show the film formed on beryllium copper and monel at a light load



(a) Beryllium copper.
(b) Monel.
(c) Nodular iron.

FIGURE 8.—Wear areas of rider specimens of various materials after 3 hours sliding against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 50 grams; X15; reduction factor, 13 percent in reproduction.

(50 grams) after 3 hours of operation without lubrication at a sliding velocity of 5000 feet per minute. In both cases the dark areas indicate the location of the film. On beryllium copper, the film formed in areas where material had rewelded to the surface. The film formed in streaks on the monel; at other stages of the experiment, the film was much more continuous than is shown in figure 8(b). The photograph of the nodular iron (fig. 8(c)), which was one of the most effective materials studied, is presented for comparison purposes.

SUMMARY OF RESULTS

An investigation of wear and friction of dry surfaces and of load capacity of boundary-lubricated surfaces of brass, bronze, beryllium copper, monel, Nichrome V, 24S–T aluminum, nodular iron, and gray cast iron sliding on hardened SAE 52100 steel was conducted. The metals investigated may be useful as possible cage materials for rolling-contact bearings of high-speed turbine engines. The research produced the following results:

1. The ability of materials to form surface films that prevent welding is a most important factor in both dry friction and boundary lubrication. These surface films were probably supplied from within the structure of the cast irons by graphitic carbon and of the bronze, by lead. Monel, Nichrome V, and beryllium copper formed films, believed to be oxides, under dry and lubricated conditions. When present, the films improved the performance of these materials.

2. On the basis of wear and resistance to welding only, cast irons were the most promising materials investigated. They showed the least wear and the least tendency toward surface welding of any of the materials when run dry. The same observations were made for boundary lubricated conditions where it was established that the cast irons had the highest load capacities of all the materials. Nodular iron has physical properties that are superior to those of gray iron.

3. The performance of monel and Nichrome V depended on whether or not a film was present but the materials with films had relatively high load capacity when boundary lubricated.

4. Bronze had the lowest friction coefficient under dry sliding conditions; however, it was subject to surface failure and increasing friction as the sliding conditions became more severe.

5. Brass, beryllium copper, and 24S–T aluminum showed continuous failure under all conditions investigated.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, *March 26, 1951*

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TABLE I—TYPICAL VALUES FOR PROPERTIES OF MATERIALS

Material	Property									Reference
	Nominal composition (percent)	Tensile strength (lb/sq in.)	Yield strength (lb/sq in.)	Brinell hardness	Modulus of elasticity	Density (lb/cu in.)	Coefficient of thermal expansion[a] (in./in./°F)	Coefficient of thermal conductivity (Btu/sq ft/hr/°F/in.)	Melting point (°F)	
Brass (cold drawn)	65 Cu 35 Zn	70×10^{3}	65×10^{3}	140	14×10^{6}	0.306	11.2×10^{-6} [b](32°–212°F)	830 [b](32°–212°F)	1710	5
Bronze (cast)	82.5 Cu 7.5 Pb 7.5 Sn 2.5 Zn	33.9×10^{3}	15.9×10^{3}	53	10.9×10^{6}	[c]0.314	[c]10.2×10^{-6} [b](32°–212°F)	[c]1100 [b](32°–212°F)	[c]1830	6
Beryllium copper (cold drawn)	97.4 Cu 2.25 Be 0.35 Co	190×10^{3}	97×10^{3}	340	18×10^{6}	0.318	9.2×10^{-6} [b](32°–212°F)	650 [b](32°–212°F)	1750	5
Monel (wrought)	67.0 Ni 30.0 Cu 1.4 Fe 1.0 Mn	110×10^{3}	100×10^{3}	[d]240	26×10^{6}	0.319	7.8×10^{-6} [b](32°–212°F)	180 [b](32°–212°F)	2460	5
Nichrome V (wrought)	80 Ni 20 Cr	110×10^{3}	63×10^{3}	90	31×10^{6}	0.303	9.8×10^{-6} [b](70°–1500°F)	166 [b](104°–212°F)	2550	6
24S–T Aluminum (wrought)	93.4 Al 4.5 Cu 0.6 Mn 1.5 Mg	68×10^{3}	44×10^{3}	105	10.3×10^{6}	0.100	13.3×10^{-6} [b](68°–392°F)	1,300 [b](room temperature)	[c]1100	6
Nodular iron (cast)	4.0 C 1.0 Mn 2.0 Si $<$0.15 P $<$0.015 S 0.06 Mg	$70–90\times10^{3}$	$45–60\times10^{3}$	217–253	$22–24\times10^{6}$	[c]0.260	[c]6.0×10^{-6}	[c]310	[c]2150	([e])
Gray cast iron	3.95 C 0.6 Mn 2.95 Si 0.6 P 0.1 S	$40–45\times10^{3}$	------------	240	$16–17\times10^{6}$	0.260	[c]5.5×10^{-6} [b](room temperature)	[c]290–360 [b](50°–450°F)	2150	([f])

[a] For comparison with the expansion coefficient of SAE 52100 steel (6.49×10^{-6} in./in./°F from 77°–300°F).
[b] Applicable temperature range.
[c] Estimate, based on similar materials.
[d] Measured value.
[e] Ford Motor Company, Dearborn, Michigan.
[f] Koppers Company, Inc., Baltimore, Maryland.